The Astrophysical Journal Supplement Series, 73:253–258, 1990 June


# THE RELATIONSHIP BETWEEN ENERGETIC PARTICLES AND FLARE PROPERTIES FOR IMPULSIVE SOLAR FLARES

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*Received 1988 December 14; accepted 1989 August 17*


## ABSTRACT

In previous papers we have argued for the existence of a class of solar energetic particle events with different properties from "normal" energetic proton events. The "impulsive" events are associated with type III/V bursts and impulsive flares and have low proton to electron ratios. We have further investigated the impulsive mode of particle acceleration by looking for 0.2–2 MeV electron increases associated with intense type III/V bursts. We find that the presence of a type III/V burst in association with a relatively intense flare event indicates the acceleration and escape of greater than 100 keV electrons. We assembled a list of type III/V electron events. For the majority we found we could also detect greater than 10 MeV proton increases despite the fact that not all the type III/V bursts were followed by type II bursts; i.e., a type II burst is not a necessary condition for the production of protons. However, events with type II bursts do have higher proton fluxes, and their spectra extend to higher energies. We find that the proton intensities are correlated with the duration of the associated H$\alpha$ flare. The results of our study are best interpreted in terms of two different modes of proton acceleration with the second mode becoming significant only for larger, more gradual flares.


*Subject headings:* Sun: flares — Sun: particle emission — Sun: radio radiation — Sun: X-rays

## I. INTRODUCTION

Recent work has shown the invalidity of the long-standing belief that particles accelerated in the so-called "first" or "impulsive" phase of solar flares, consist only of electrons with maximum energies of the order of 100 keV (Wild, Smerd, and Weiss 1963). The *SMM* gamma-ray spectrometer showed that gamma-rays and neutrons are first-phase phenomena (Forrest *et al.* 1981). Protons of at least 10 MeV are required to explain gamma-ray lines, and neutrons imply the presence of protons to hundreds of MeV. It has been argued (Cane, McGuire, and Von Rosenvinge 1986; hereinafter CMvR) that the impulsively accelerated higher energy particles can be detected in space. Sometimes these particles cannot escape, but more often they cannot be distinguished from the "second-phase" particles which are more abundant. Since the second-phase acceleration occurs primarily in gradual flares, first-phase particles are more readily distinguished in impulsive flares. In fact, CMvR suggested that for any particular interplanetary electron event the responsible mechanism or phase could usually be determined from the time scale of the flare.

CMvR argued that generally, for particle events associated with impulsive flares the acceleration mechanism does not involve a coronal shock. Shock acceleration is assumed responsible for "normal" high-energy proton events. The signature of a coronal shock is a type II radio burst. However, rather than type II, type IV radio emission is a better signature of the occurrence of this "second phase" or mode of acceleration (Kahler 1982*a*). Type IV emission appears to indicate the existence of the required conditions for efficient shock acceleration to take place. Whereas the archetypal signature of the impulsive phase is the type III meter-wavelength radio burst, CMvR showed that the signature of high-energy particle production and escape to the interplanetary medium was an intense type III burst followed by type V continuum. An association between type III/V bursts and gamma-ray events was also suggested by Raoult *et al.* (1985).

In a recent study Cane and Reames (1988) examined the relationship between meter wavelength radio bursts of types II and IV and the time scales of the associated soft X-ray flares. The study also included a smaller sample of type III/V bursts. It was shown that 86% of type III/V bursts (indicating first phase acceleration) are associated with impulsive (soft X-ray duration < 1 hr) flares, whereas 53% of type IV bursts (indicating second-phase acceleration) are associated with gradual flares. Because of the overlap in the durations of flares associated with the different radio bursts it was suggested that meter-wavelength radio data in conjunction with soft X-ray data provided a better understanding of the processes occurring in a particular solar event rather than the flare time scale alone.

For many events it is possible to distinguish the dominant phase of acceleration by observing the abundances of heavy elements or the presence of $^3$He (see reviews by Lin 1987 and Reames 1990). A $^3$He-rich, Fe-rich population of energetic particles is attributed to wave-particle interactions in flare-heated material accelerated in impulsive events. Particles from the second phase have abundances that are representative of ambient coronal material accelerated away from the flaring region. A general relationship has been observed between enhancements in electron to proton ratio and those in $^3$He/$^4$He or Fe/O (Reames 1988).

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The study of CMvR looked at high-energy ( > 3 MeV) electron events detected by an experiment on the *IMP 8* spacecraft and found 31 events associated with X-ray flares with durations of less than 1hr. We sought to further investigate the results by obtaining a larger sample of less energetic events. In a different approach we attacked the problem by commencing with intense type III/V bursts. We used the 0.2–2 MeV electron channel on *ISEE 3* to identify associated particle increases. Starting with the radio bursts ensured that some, if not all, of the associated particles in each event would be from the "impulsive" phase. If one starts with all electron events there will be a mixture of impulsive and gradual events as was found by CMvR. We also wanted to determine what subset of radio bursts give rise to observable electron events.

## II. DATA ANALYSIS

The study began by assembling a list of all strong type III bursts accompanied by type V emission for a period of ~ 4.5 yr commencing 1978 September. We used Solar Geophysical Data (SGD) and reports by the Culgoora, Harvard, and Weissenau observatories and obtained a list of ~ 1300 bursts. Not included were events with durations less than a minute or intensity class of less than 2. Thus the vast majority of events with type V bursts were included.

At the times of all the radio bursts we looked for 0.2–2 MeV electron increases detected by the Goddard Space Flight Center experiment on *ISEE 3*. We found that for about half of the time it was not possible to determine whether an associated event was present or not because of a

bursts with H$\alpha$ flares, 42% of these flares are classified as "bright" and 95% are of importance class "1" or "-" (Cane 1989).

We also associated the type III/V/electron events with soft X-ray flares using the six day plots in SGD. Apart from six events with data gaps it was possible to associate all the events which were also associated with an H$\alpha$ flare and also five other events. Eighty-two percent (53 of 65) of the associated X-ray increases were greater than $9 \times 10^{-6}$ W m$^{-2}$ (denoted C9 on the CMX scale). In contrast less than 30% of all type III/V radio bursts can be associated with greater than C9 soft X-ray flares (Cane 1989).

Our results suggest that particle events are associated with the more energetic flares and that more particle events would be detected with more sensitive instruments. The detection of particles also depends on good connection to the source region. Both these properties are shown in Table 1 where the distribution of type III/V bursts with "useful" electron data are given. "Useful" data means that we could tell whether there was an increase or not which required that there had to be ($a$) data and ($b$) a low background intensity. These conditions applied to less than 50% of our original sample of 1300 radio bursts and the number of events in Table 1 is even less since we also required a distinguishable X-ray event. Recall also that six type III/V electron events occurred during an X-ray data gap. It can be seen that there are four radio bursts associated with intense flares occurring in a favorable location which were not associated with a particle event. In these events it is probable that the interplanetary magnetic field from the flare site did not intercept the Earth. One of the first gamma-ray line events detected by

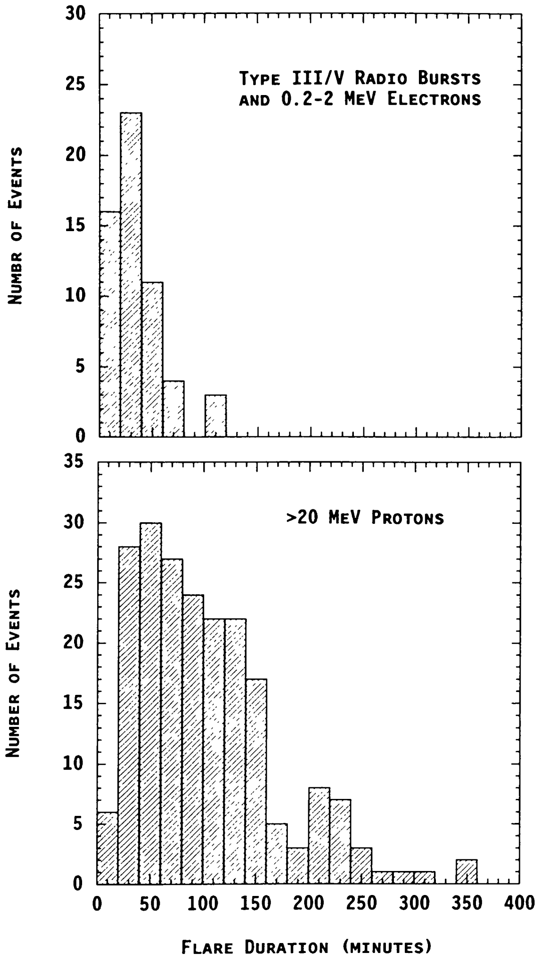


FIG. 1.—The distributions of the durations in minutes of H$\alpha$ flares associated with ($a$) type III/V bursts and 0.2–2 MeV electron increases and ($b$) > 20 MeV proton events. Some of the events are common to both panels.

the plots the number will be less than this because of missing data; e.g., H$\alpha$.

Figure 1 shows the H$\alpha$ flare durations for 57 type III/V electron events. For comparison we show the durations of flares associated with all proton events greater than 20 MeV detected in the period 1967 May to 1985 December. The proton list was obtained in a previous study (Cane, Reames, and Rosenvinge 1988). Some events of Figure 1$b$ are common to Figure 1$a$.

For the majority of the type III/ V electron events we detected protons above ~10 MeV. There were 18 events for which we could not tell if there was a proton increase either because of a data gap or because of a high background level. There were 10 events which showed no increase above the normal quiet-time background for 7–12 MeV protons. Figure 2 shows the electron and 7–12 MeV proton intensities as a function of flare duration. In the figures we have used symbols representing the presence and intensity of associated type II bursts. Note that of the 45 events with detectable 7–12 MeV protons, 11 have no associated type II burst, contrary to the long-held view that a type II burst is a necessary condition for the production of interplanetary protons. Of the total list of type III/V electron events 37% (29 of 78) have no associated type II burst. The number may be even larger, since we have been very liberal in designating the presence of a type II burst. For some events what was actually reported was "unclassified" activity.

Figure 3 shows 30–45 MeV proton intensities as a function of electron intensities. Twenty of our 73 events showed no increase above quiet-time background ($\sim 2\times10^{-4}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ MeV$^{-1}$) but these upper limits are shown on the plot. In order to show where "normal" proton events lie on such a plot we have added the six events from CMvR which were associated with gradual flares and which had strong type III bursts but no type V.

Figure 4 shows the electron to proton ratio (e/p) versus the flare duration. For this parameter the 7–12 MeV proton intensities were used. The events without associated type II bursts are indicated with the plus symbol.

Figure 5 shows the electron intensities as a function of the soft X-ray peak intensity. The correlation is not strong but the important feature is the absence of events in the top left of the figure. There are no large impulsive electron events associated with weak flares. For comparison we show a similar plot for the complete greater than 20 MeV proton-event list referenced earlier.

As mentioned in the introduction it has been shown that many impulsive events have high abundances of $^3$He relative to $^4$He. We examined each of the 73 events of the present study for increases in He in the 1.3–1.6 MeV/amu interval and determined $^3$He/$^4$He where possible. Of the 73 events 63 had measurable He abundances. Of the 63 events, 46 had statistically valid ratios, $^3$He/$^4$He above ~0.05. For the remaining 17 events it is only possible to say that $^3$He/$^4$He < 0.05 because of limitations in the instrument resolution. However these events could still be "$^3$He-rich" relative to the solar wind where $^3$He/$^4$He is $5\times10^{-4}$.

## III. DISCUSSION AND CONCLUSION

We have obtained a list of electron events greater than 200 keV which are associated with type III/V bursts. We found 78 events, of which 71 could be associated with a flare (i.e., H$\alpha$ or soft X-ray event), for a period of 52 months. Our original sample of radio bursts had a rate of ~12 per month associated with a disk flare event. Assuming that only those events which were intense (i.e., M1 or greater in soft X-rays) and originating within $\pm30°$ of the nominal "best connection" of W60°, one expects $12\times0.3\times0.3=1$ event per month. Furthermore, we found that for about half of the time it was not possible to determine whether an associated event was present or not because of a high background from a prior large event. Thus we believe that we have found all of the particle events expected for the solar events satisfying our criteria. This suggests that electrons greater than 200 keV should be detectable in space (at an appropriate location) from all intense flare events exhibiting a type III/V radio burst. We showed in Figure 1 that such flares are generally impulsive (H$\alpha$ duration less than 60 minutes). In contrast, solar events generating protons greater than 20 MeV are generally gradual, as may also be seen in Figure 1.

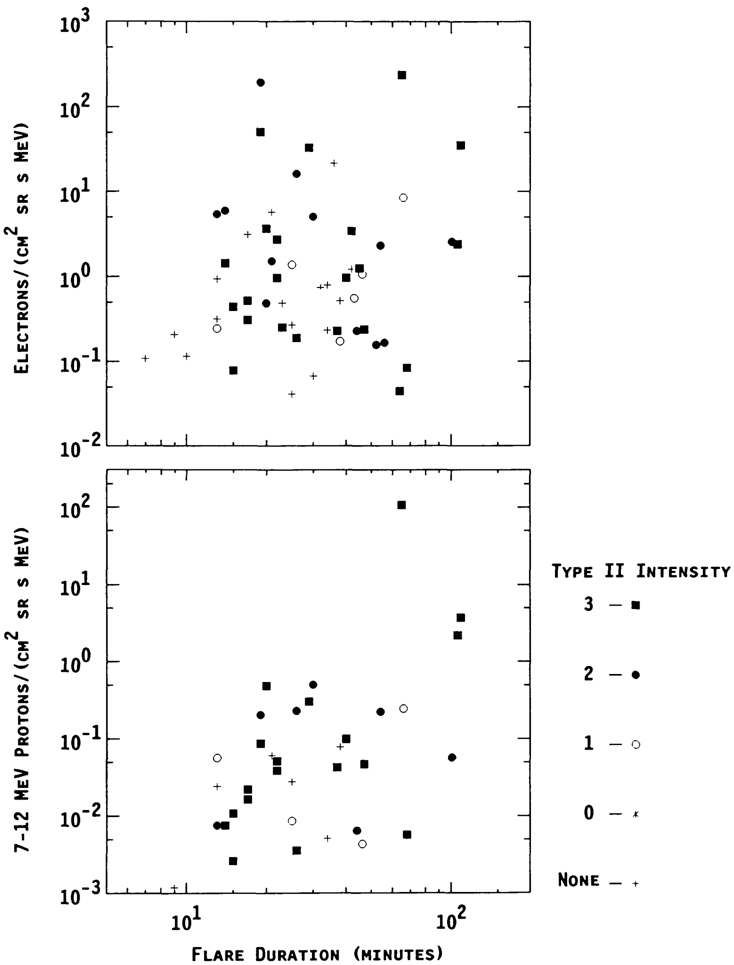


FIG. 2.—0.2–2 MeV electron and 7–12 MeV proton intensities as a function of flare duration. The pluses denote events with no associated type II burst. The asterisks, open circles, filled circles, and filled squares denote events with associated type II bursts of intensity class 0 ( = weak), 1, 2, and 3, respectively.

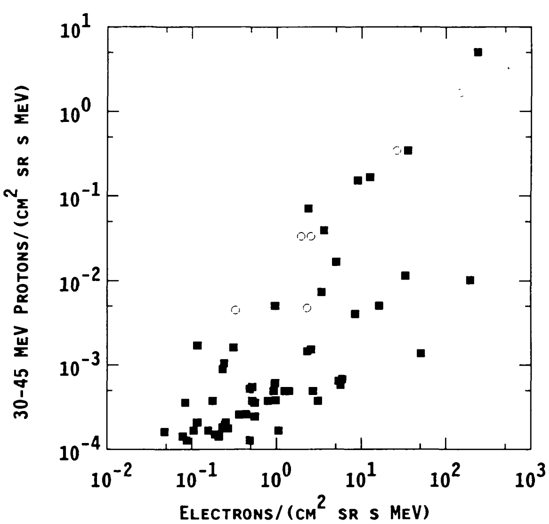


FIG. 3.—30–45 MeV proton intensities vs. electron (0.2–2 MeV) intensities. The open circles represent six large proton events added to show the distribution of such events.

Figure 3 illustrates the problem of attempting to separate particle events into two separate groups. The majority of the type III/V electron events show a proton intensity versus electron intensity distribution which is different from the distribution for large proton events. However, a number of type III/V electron events have relatively high 30–45 MeV proton intensities; six events have intensities above $2 \times 10^{-2}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ MeV$^{-1}$. Three of these are associated with flares of durations longer than 60 minutes, and based on this we would assume that the particles are predominantly second phase. For one event we have no flare information. There remain two events associated with impulsive flares (H$\alpha$ durations of 20 and 30 minutes) with high proton intensities. We note, however, that for at least one event the composition would suggest that the particles come from the first phase. The background is too high to determine the composition of the remaining event.

The distribution of e/p values showed a continuous change with flare duration. We did not expect a bimodal distribution because of the varying contributions from first- and second-phase processes and because electrons and protons cannot be compared in a manner that is independent of the electron and proton spectra. We find that the events without type II

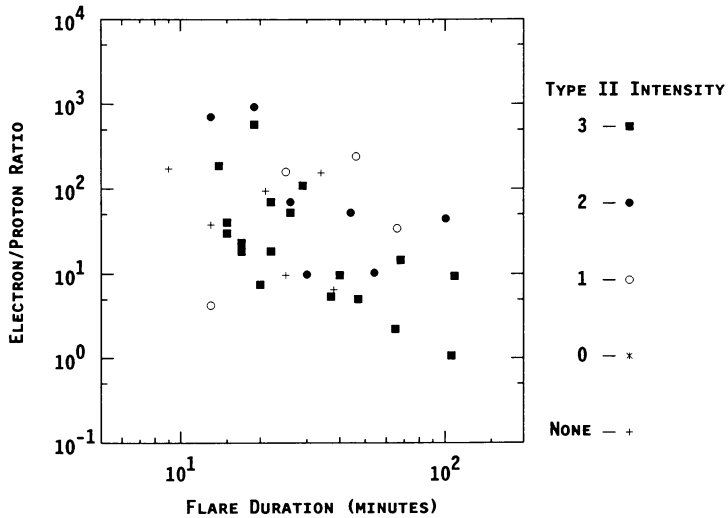


FIG. 4.—The ratio of the electron (0.2–2 MeV) intensity to the proton (7–12 MeV) intensity as a function of Hα flare duration. The symbols have the same meaning as in Fig. 2.

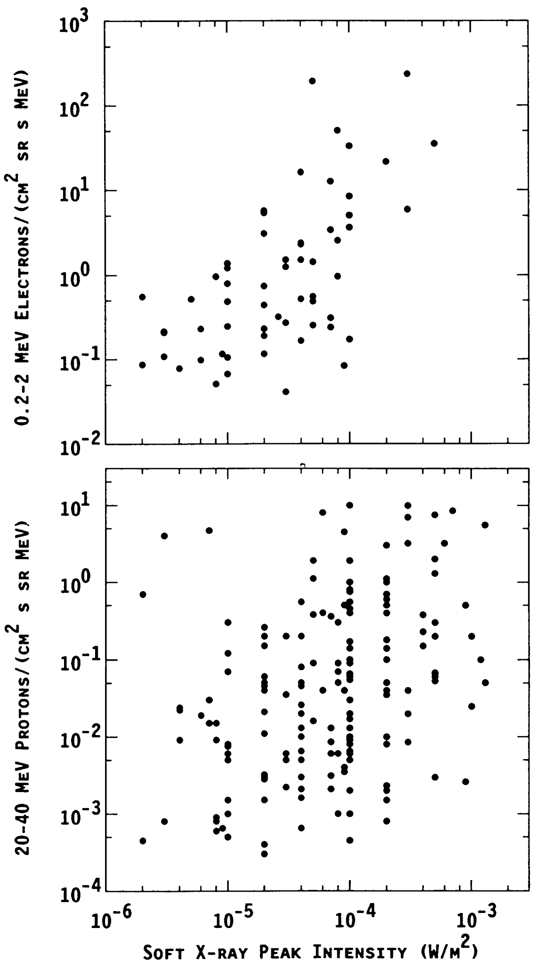


FIG. 5.—The correlation of (*a*) 0.2–2 MeV electron and (*b*) 20–40 MeV proton intensities as a function of the soft X-ray intensities of associated flares.

bursts fall within the distribution for those with type II bursts.

The relationship between the electrons greater than 200 keV and flare heating, as indicated by soft X-rays, was examined. The correlation between the observed electron fluxes and the X-ray intensities was not strong. In fact, it would be surprising if it were, given the presumed variable escape fraction from event to event and the effect of not always sampling the center of the electron beam, along with the energy difference of the observations. However, in contrast to large proton events there are no intense electron events associated with relatively weak soft X-ray events. There exist large proton events associated with weak flares (see Fig. 5 and Cliver, Kahler, and McIntosh, 1983; Cane, Kahler, and Sheeley 1986) and it has been argued (Cliver *et al.* 1983; Kahler, 1982*b*) that the acceleration process responsible for proton acceleration is not intimately connected with the flare emissions. One could not make this argument for the electron events studied here.

The most intense impulsive events produce gamma-ray lines by nuclear interactions and, not surprisingly, the majority of those large events also have associated type II bursts. It has been proposed (Bai and Dennis 1985) that there is a second "step" in impulsive acceleration in which shocks accelerate the protons that are responsible for the gamma-ray lines. This idea then maintains the electron "pureness" of the impulsive phase (although we observe protons in a number of events with no type II bursts). If a shock had sufficient strength to produce energetic protons inside a flare loop where the gamma rays originate it would also be expected to produce them outside the loop. Consequently one would expect the interplanetary e/p ratio for gamma-ray line events to be the same as for normal proton events and different from electron events without associated type II bursts. This is not the case (Evenson *et al.* 1984) and suggests that the type II burst is not responsible for proton acceleration in gamma-ray line events. In an alternative model described by

Miller and Ramaty (1987), protons in these events are accelerated stochastically by interactions with a Kolmogorov spectrum of Alfvén waves while electrons are accelerated primarily by whistler waves.

In summary, the presence of a type III/V burst in association with a relatively intense flare event indicates the acceleration and escape of greater than 100 keV electrons. In general, protons of at least 10 MeV are also accelerated. The impulsive acceleration mechanism therefore is not restricted to only low-energy ( < 100 keV) electrons. Events with coronal shocks, as indicated by the presence of type II bursts, are associated with more gradual flares and accelerate increasingly proton-rich material.

We thank an anonymous referee for many useful comments which substantially improved the manuscript.

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